

COMMON ENVELOPE EVOLUTION LEADING TO SUPERNOVAE WITH DENSE INTERACTION

Roger A. Chevalier

*Department of Astronomy, University of Virginia, P.O. Box 400325,
Charlottesville, VA 22904-4325; rac5x@virginia.edu*

ABSTRACT

A variety of supernova events, including Type IIn supernovae and ultraluminous supernovae, appear to have lost up to solar masses of their envelopes in 10's to 100's of years leading up to the explosion. In order to explain the close timing of the mass loss and supernova events, we explore the possibility that the mass loss is driven by common envelope evolution of a compact object (neutron star or black hole) in the envelope of a massive star and the supernova is triggered by the inspiral of the compact object to the central core of the companion star. The expected rate of such events is smaller than the observed rate of Type IIn supernovae but the rates may agree within the uncertainties. The mass loss velocity is related to the escape velocity from the common envelope system and is comparable to the observed velocity of 100's of km s^{-1} in Type IIn events. The mass loss is expected to be denser near the equatorial plane of the binary system and there is good evidence that the circumstellar media in Type IIn supernovae are asymmetric. Some of these supernova types show evidence for energies in excess of the canonical 10^{51} ergs, which might be the result of explosions from rapid accretion onto a compact object through a disk.

Subject headings: binaries: close — circumstellar matter — supernovae: general

1. INTRODUCTION

There is growing evidence for some supernovae exploding into a medium that is much denser than the stellar winds that might be expected around a normal star. In Type IIn (narrow line) supernovae (Schlegel 1990), the optical luminosities are plausibly explained as being due to circumstellar interaction and the circumstellar density can be estimated from the luminosity (Chugai & Danziger 1994). If narrow line widths are indicative of the presupernova outflow velocities, the typical outflow velocities are $100 - 500 \text{ km s}^{-1}$, leading

to times of mass loss before explosion of $10 - 300$ yr and mass loss rates of $0.02 - 0.1 M_{\odot} \text{ yr}^{-1}$ for typical Type IIn supernovae (SNe IIn) (Kiewe et al. 2012). The mass loss can be up to several M_{\odot} extending out as far as 10^{17} cm.

The class of ultraluminous supernovae overlaps the SNe IIn, with objects like SN 2006gy that was very bright for 240 days and radiated $\gtrsim 2 \times 10^{51}$ ergs in optical light (Miller et al. 2010). Another group of the ultraluminous events are not SN IIn, but have spectra that resemble SNe Ic at later times (Quimby et al. 2011; Pastorello et al. 2010). Chevalier & Irwin (2011) suggested that the ultraluminous supernovae are due to dense circumstellar interaction, but only ones with a circumstellar extent greater than the radius at which radiation can diffuse out have Type IIn characteristics. The mass loss involved can be $\gtrsim 10 M_{\odot}$ and extends to $\gtrsim 2 \times 10^{15}$ cm for Type IIn characteristics (see also Smith & McCray 2007).

To account for such high mass loss rates, luminous blue variable (LBV) progenitors have been suggested (Smith 2010; Kiewe et al. 2012, and references therein). In the case of SN 2005gl, a progenitor object was observed that is consistent with an LBV (Gal-Yam & Leonard 2009). However, the LBV possibility does not answer the question of why is the explosion so well synchronized with the strong mass loss event; the LBV phase is expected to be followed by a Wolf-Rayet phase lasting $10^5 - 10^6$ yr. Another point is that LBVs are associated with very massive stars ($\sim 30 - 80 M_{\odot}$), but the stellar populations around SNe IIn are comparable to those around SNe II in general, which typically come from lower mass stars (Kelly & Kirshner 2011; Anderson et al. 2012). These results for the Type IIn are distinct from the Types IIb and Ib/c which show a clear connection to star forming regions. The implication is that SN IIn progenitors are not confined to very high mass stars, but may cover a broad range of stellar masses (Kelly & Kirshner 2011; Anderson et al. 2012).

These properties argue against a particular mass range becoming a supernova, and indicate that some factor other than mass plays a role. Here we suggest that the factor is binarity and that the mass loss and explosion are both driven by the inspiral of a compact object in common envelope (CE) evolution (Section 2). This explosion mechanism has been previously considered by Fryer & Woosley (1998), Zhang & Fryer (2001), Barkov & Komissarov (2011), and Thöne et al. (2011). The implications of the CE mass loss for Type IIn supernovae and related objects are presented in Section 3. General aspects of the mechanism are discussed in Section 4.

2. COMMON ENVELOPE EVOLUTION AND EXPLOSION

The suggested sequence of events leading to supernovae with dense environments is shown in Figure 1. The starting point is two massive stars in a binary. The more massive star evolves, transfers mass to its companion, and explodes as a supernova, leaving a neutron star (NS) or, less likely, a black hole (BH). In the cases where the NS remains bound in a close orbit to the companion star, the binary enters a common envelope (CE) phase when the companion evolves and expands. Depending on the initial separation, the CE phase starts only when the companion becomes a red supergiant, or at an earlier phase if the binary is tighter. During the inspiral phase, the Bondi-Hoyle accretion rate is well above the $10^{-3} M_{\odot} \text{ yr}^{-1}$ limit for spherical neutrino cooled accretion (Chevalier 1993). However, angular momentum of the accreting material can prevent the high pressures needed for neutrino emission (Chevalier 1996) and numerical simulation of CE evolution show that the accretion rate can be significantly smaller than the Bondi-Hoyle value (Ricker & Taam 2012). Whether neutrino cooled accretion can occur during spiral in through the envelope is controversial (Fryer & Woosley 1998; Barkov & Komissarov 2011), but the outcome is not crucial to the present arguments.

The initial progress of the inspiral process depends on the density profile in the companion star (Taam & Sandquist 2000). A red supergiant has a moderately flat density profile in the envelope, leading to strong interaction followed by weak interaction and envelope ejection, and leaving a NS/He star binary (Figure 1). Because CE evolution with a red supergiant occurs over a relatively small range of separations, it is more likely that the CE phase occurs at an earlier evolutionary phase when there is a steady gradient from the center to the edge of the star, and inspiral does not stop outside the stellar core.

A possible outcome of the inspiral to the central core is the formation of a Thorne-Zytkow object (TZO, Thorne & Zytkow 1977): an extended star with a NS core. TZOs have not been observationally identified, so their existence remains uncertain. Chevalier (1996) argued that inspiral in the core of the companion would lead to rapid, neutrino-cooled accretion and collapse to a black hole because of the high densities present there. For inspiral in a He star, (Fryer & Woosley 1998) estimated accretion rates as high $3 \times 10^7 M_{\odot} \text{ yr}^{-1}$, leading not only to BH formation but also strong explosions. SPH simulations of the process by Zhang & Fryer (2001) showed accretion rates of $10^5 - 10^6 M_{\odot} \text{ yr}^{-1}$, sufficient for a 10^{51} erg explosion. In the present scenario, the interaction of such an explosion with the mass lost during the initial CE phase is potentially a Type IIn supernova. Figure 1 shows the TZO and SN outcomes of central inspiral; additional possible outcomes are BH without a supernova or a magnetar that was spinning rapidly enough to eject surrounding material.

The expansion velocity that is expected from common envelope evolution is of order the

escape velocity from the extended star (Terman et al. 1995; Taam & Sandquist 2000). For a red supergiant companion, this is $\lesssim 100 \text{ km s}^{-1}$ which is low for a Type II in circumstellar medium, but this evolution channel is expected to lead to a He star/compact object binary and not directly to a supernova. The lifetime of the He star is $\lesssim 10^5 \text{ yr}$, so that the radius of the H envelope at the time that the He star reaches its advanced burning phases is $\sim 10^{19} \text{ cm}$. For CE evolution at an earlier evolutionary phase, the star is more compact and the escape velocity is higher. For example, in case 1 of Terman et al. (1995), the $16 M_{\odot}$ star has a radius of $2 \times 10^{12} \text{ cm}$ and the escape velocity is 430 km s^{-1} . It is the more compact cases in which the compact object can continue to spiral in to the core and give rise to a supernova in the present scenario.

Another factor for determining the disposition of the circumstellar matter at the time of the explosion is the time between the beginning of mass loss and the explosion. The explosion depends on the rapid accretion of matter onto the black hole, which occurs only when the BH has reached the central region of the stellar core, although scenarios with slower accretion leading to a magnetar may also be possible (Barkov & Komissarov 2011). The timescale for inspiral to occur is $\lesssim 10^3 \text{ yr}$ (Taam & Sandquist 2000). The timescale for the initial orbit decay is $\sim 200 \text{ yr}$ for a star in its early core He burning phase, but $\sim 3 \text{ yr}$ for a star in its late core He burning phase, because of the difference in the density distribution (Terman et al. 1995; Taam & Sandquist 2000).

An expectation for mass lost during the common envelope phase is that it is concentrated toward the orbital plane of the binary (Terman et al. 1995; Taam & Ricker 2010). In 3-dimensional simulations involving a $1.05 M_{\odot}$ red giant and a lower mass companion, Ricker & Taam (2012) find that 90% of the mass outflow is in a region 30° about the orbital plane. Figure 7 of Ricker & Taam (2012) indicates that the mass per unit solid angle in the equatorial direction is 20 times that in the polar direction. The degree of asymmetry depends on the mass ratio (secondary to primary), with a small ratio giving a higher degree of asymmetry. In the case of a ratio near unity, the stellar core is spun up by the companion, leading to a broad flow with an evacuated region along the poles (Taam & Ricker 2010). In the case considered here, the mass ratio is fairly small.

For systems that form a stable He star/neutron star binary, the further possibilities for the binary are inspiral into the He star, or the explosion of the He star leading to two compact objects either bound or unbound (Figure 1). In the present scenario, the channel that leads to inspiral in the He star can give rise to H-free luminous supernovae (Quimby et al. 2011; Pastorello et al. 2010) and possibly Type Ibn supernovae (Pastorello et al. 2008) or low luminosity gamma-ray bursts (GRBs) (Thöne et al. 2011).

3. COMPARISON WITH TYPE II_n AND RELATED SUPERNOVAE

The basic properties of SNe II_n surroundings given in Section 1 (velocity, mass, and timescale) are in rough agreement with mass loss during a CE phase. The extent of the mass loss is important for the supernova properties. If the extent is relatively small ($\sim 1 \times 10^{16}$ cm), the supernova is very luminous for a relatively short time (~ 240 days as for SN 2006gy (Miller et al. 2010)), while if the extent is large ($\sim 1 \times 10^{17}$ cm), the supernova is less luminous but for a long time (10 yr as for SN 1988Z (Aretxaga et al. 1999)). In both of these cases, the observed radiated energy is $\gtrsim (1 - 2) \times 10^{51}$ erg.

A further consequence of the CE scenario for the formation of the circumstellar medium is that it should have higher density in the equatorial plane. The possibility that SN II_n involve interaction with equatorial mass loss was already suggested by Chugai & Danziger (1994) to explain the intermediate velocity (~ 2000 km s⁻¹) component in spectra of SN 1988Z. The presence of both high velocity and intermediate velocity components required either a clumpy circumstellar medium or an asymmetric flow. Chugai & Danziger (1994) preferred the clumpy wind model because the mass loss rate required by the equatorial flow model ($0.015 M_{\odot}$ yr⁻¹) was considered too high. However, this rate is in keeping with expectations for a CE phase of evolution. The most direct evidence for asymmetric interaction comes from polarization measurements. High polarization at optical wavelengths has been observed in the SNe II_n that have been studied (Patat et al. 2011, and references therein). The continuum polarization is likely due to electron scattering in an asymmetric circumstellar medium, suggesting an axial ratio $\lesssim 70\%$ in the case of SN 2010jl (Patat et al. 2011).

Chugai & Danziger (1994) note that a distinction between the clumpy and equatorial structure is that the intermediate component emission is near the outer shock in the clumpy case, but is at a relatively small radius (corresponding to the velocity) in the equatorial case. It has not been possible to spatially resolve the intermediate component optical emission in any SN II_n, but it has been possible to resolve the radio emission from the nearby Type II_n SN 1986J with VLBI techniques (Bietenholz et al. 2010). In the case of SN 1986J, the width of the “intermediate width” H α line was ~ 1000 km s⁻¹ (FWHM) at an age of 3 yr (Rupen et al. 1987) and remained narrow at 24 yr (Milisavljevic et al. 2008). Recent radio observations show a centrally located source that is marginally resolved at 5×10^{16} cm (Bietenholz et al. 2010), corresponding to an average radial velocity of 340 km s⁻¹ at an age of 23 yr. It is possible that the central emission is associated with the inner equatorial interaction region.

To estimate the rate of the mergers of NSs with stars, we use previous estimates of the rate of formation of TZOs because we are following the hypothesis that evolution leading to these objects can instead lead to supernovae. Based on numbers of high mass X-ray

binaries, Podsiadlowski et al. (1995) estimated a rate of TZO formation in the Galaxy of $\gtrsim 2 \times 10^{-4} \text{ yr}^{-1}$, which includes inspiral events and mergers due to the direction of the neutron star kick during formation. The core collapse supernova (CCSN) rate in the Galaxy is $(2.30 \pm 0.48) \times 10^{-2} \text{ yr}^{-1}$ and the SN II rate is $(1.52 \pm 0.32) \times 10^{-2} \text{ yr}^{-1}$ (Li et al. 2011b). Li et al. (2011a) find that $8.6^{+3.3}_{-3.2}\%$ of SN II are of Type IIn, leading to a SN IIn rate of $13 \times 10^{-4} \text{ yr}^{-1}$, while Smartt et al. (2009) find that 3.8% of CCSN are IIn, leading to a IIn rate of $8.7 \times 10^{-4} \text{ yr}^{-1}$. The Type IIn rate in the Galaxy may be somewhat decreased because IIn events preferentially occur in low mass galaxies (Li et al. 2011a). The result is that the merger rate falls short of the SN IIn rate, but the substantial uncertainty in the rates might allow the events to be associated.

As noted above, the rate of inspirals stopping outside the core is expected to be smaller than the rate of inspirals continuing into the core (Figure 1). Binary NS or BH systems should thus form less frequently than central inspirals. The rate of formation of binary compact objects (NS or BH) by the channel shown in Figure 1 is estimated at $\sim 0.9 \times 10^{-4} \text{ yr}^{-1}$ in binary population models (Belczynski et al. 2002).

4. DISCUSSION

There is good evidence that the most luminous SNe IIn occur in low metallicity regions (Neill et al. 2011). In the scenario suggested here, this property can be attributed to the dependence of mass loss on metallicity. At solar metallicity, stars with masses above $\sim 35 M_{\odot}$ do not become red supergiants, but remain relatively compact because of mass loss. At low metallicity, this mass limit is expected to increase and more massive stars become extended. The expansion in radius is needed to enter the CE phase, so more massive stars can experience spiral in and explosion at low metallicity. These stars have more mass loss and more massive black holes, so that more luminous supernovae are expected.

The energies of well-observed Type II supernovae, including SN 1987A and SN 1993J, are $\sim 1 \times 10^{51}$ ergs, while high energies, $\gtrsim 10^{52}$ ergs, have been inferred for some Type Ic supernovae that are associated with GRBs (e.g., Figure 8 in Tanaka et al. 2009). In the GRB case, the high supernova energy is presumably associated with the central engine, but the exact mechanism for the high energy is not understood. High energies have also been inferred for SNe IIn primarily from their radiated energy, e.g., SN 1998Z is estimated to have had a total radiated energy as high as 5×10^{51} (Aretxaga et al. 1999) and the explosion energy must have been significantly higher. A high explosion energy does not appear to be due to a highly massive star progenitor; the interaction properties of SN 1988Z indicate an ejecta mass $\lesssim 1 M_{\odot}$ (Chugai & Danziger 1994). The link between central engines and

energetic supernovae may extend to SNe IIn.

A clearer connection to a rapidly rotating central engine would be evidence for a jet-like flow in a SN IIn. Although there have been suggested associations of SNe IIn with GRBs, e.g. SN 1997cy (Germany et al. 2000), there have been no convincing associations, which can be attributed to there being too much surrounding dense material for a relativistic flow to propagate. However, the Type IIn SN 2010jp shows evidence for a nonrelativistic jet-like flow (Smith et al. 2012).

The Type IIn phenomenon has also been observed in association with Type Ia supernovae, starting with SN 2002ic (Hamuy et al. 2003). The scenario of CE mass loss followed by a supernova can also be considered for the white dwarf case. A white dwarf spirals into the envelope of an evolved companion and continues to the core where strong accretion gives rise to a thermonuclear explosion. This scenario would be compatible with a double degenerate origin for Type Ia supernovae, as discussed by Livio & Riess (2003).

The proposal made here about the origin of the dense matter around Type IIn and related supernovae is speculative, but shows some promising points of comparison. The possibility that CE evolution leads to the matter has long been mentioned (Chugai & Danziger 1994). The hypothesis that the mass loss and supernova both result from CE evolution has been raised by Barkov & Komissarov (2011) and (after this paper was submitted) by Soker (2012), but has not been much explored. There are other suggestions for the presence of the dense matter near a SN IIn. Metzger (2010) proposed disk material that has survived from the formation phase; however, the narrow P Cygni lines that are observed in SNe IIn are generally taken to imply outflowing dense material, and there is no direct evidence for such disks around massive stars. Quataert & Shiode (2012) proposed mass loss driven by gravity waves generated in the late burning phases; however, at this point the model does not explain what are the properties of the small fraction of massive stars that end as SN IIn events. The binary model proposed here provides a natural explanation for the heterogeneity of Type IIn events. For the case of a very massive star, it explains the presence of H at the time of the supernova, which would not be present if the star ran its full evolutionary course. Whether the binary hypothesis is viable ultimately depends on a better understanding of the CE process. The process is complex, but detailed, 3-dimensional simulation are becoming feasible (Ricker & Taam 2012).

I thank Mel Davies, Mario Livio, and Ron Taam for discussions, and the referee for helpful comments. This research was supported in part by NSF grant AST-0807727.

REFERENCES

- Anderson, J. P., Habergham, S. M., James, P. A., & Hamuy, M. 2012, in Proc. IAUS 279, Deaths of Massive Stars: Supernovae and Gamma-Ray Bursts, ed. P. Roming, N. Kawai, & E. Pian (Cambridge: CUP), in press (arXiv:1204.3634)
- Aretxaga, I., Benetti, S., Terlevich, R. J., et al. 1999, MNRAS, 309, 343
- Barkov, M. V., & Komissarov, S. S. 2011, MNRAS, 415, 944
- Belczynski, K., Kalogera, V., & Bulik, T. 2002, ApJ, 572, 407
- Bietenholz, M. F., Bartel, N., & Rupen, M. P. 2010, ApJ, 712, 1057
- Chevalier, R. A. 1993, ApJ, 411, L33
- Chevalier, R. A. 1996, ApJ, 459, 322
- Chevalier, R. A., & Irwin, C. M. 2011, ApJ, 729, L6
- Chugai, N. N., & Danziger, I. J. 1994, MNRAS, 268, 173
- Fryer, C. L., & Woosley, S. E. 1998, ApJ, 502, L9
- Gal-Yam, A., & Leonard, D. C. 2009, Nature, 458, 865
- Germany, L. M., Reiss, D. J., Sadler, E. M., Schmidt, B. P., & Stubbs, C. W. 2000, ApJ, 533, 320
- Hamuy, M., Phillips, M. M., Suntzeff, N. B., et al. 2003, Nature, 424, 651
- Kelly, P. L., & Kirshner, R. P. 2011, ApJ, submitted (arXiv:1110.1377)
- Kiewe, M., Gal-Yam, A., Arcavi, I., et al. 2012, ApJ, 744, 10
- Li, W., Leaman, J., Chornock, R., et al. 2011a, MNRAS, 412, 1441
- Li, W., Chornock, R., Leaman, J., et al. 2011b, MNRAS, 412, 1473
- Livio, M., & Riess, A. G. 2003, ApJ, 594, L93
- Metzger, B. D. 2010, MNRAS, 409, 284
- Milisavljevic, D., Fesen, R. A., Leibundgut, B., & Kirshner, R. P. 2008, ApJ, 684, 1170
- Miller, A. A., Smith, N., Li, W., et al. 2010, AJ, 139, 2218

- Neill, J. D., Sullivan, M., Gal-Yam, A., et al. 2011, *ApJ*, 727, 15
- Pastorello, A., Mattila, S., Zampieri, L., et al. 2008, *MNRAS*, 389, 113
- Pastorello, A., Smartt, S. J., Botticella, M. T., et al. 2010, *ApJ*, 724, L16
- Patat, F., Taubenberger, S., Benetti, S., Pastorello, A., & Harutyunyan, A. 2011, *A&A*, 527, L6
- Podsiadlowski, P., Cannon, R. C., & Rees, M. J. 1995, *MNRAS*, 274, 485
- Quataert, E., & Shiode, J. 2012, *MNRAS*, in press (arXiv:1202.5036)
- Quimby, R. M., Kulkarni, S. R., Kasliwal, M. M., et al. 2011, *Nature*, 474, 487
- Ricker, P. M., & Taam, R. E. 2012, *ApJ*, 746, 74
- Rupen, M. P., van Gorkom, J. H., Knapp, G. R., Gunn, J. E., & Schneider, D. P. 1987, *AJ*, 94, 61
- Schlegel, E. M. 1990, *MNRAS*, 244, 269
- Smartt, S. J., Eldridge, J. J., Crockett, R. M., & Maund, J. R. 2009, *MNRAS*, 395, 1409
- Smith, N., & McCray, R. 2007, *ApJ*, 671, L17
- Smith, N., Cenko, S. B., Butler, N., et al. 2012, *MNRAS*, 420, 1135
- Smith, N. 2010, in *Hot and Cool: Bridging Gaps in Massive Star Evolution*, ed. C. Leitherer, P. D. Bennett, P. W. Morris, & J. T. van Loon (San Francisco: ASP) , 63
- Soker, N. 2012, preprint (arXiv:1204.3173)
- Taam, R. E., & Sandquist, E. L. 2000, *ARA&A*, 38, 113
- Taam, R. E., & Ricker, P. M. 2010, *New A Rev.*, 54, 65
- Tanaka, M., Tominaga, N., Nomoto, K., et al. 2009, *ApJ*, 692, 1131
- Terman, J. L., Taam, R. E., & Hernquist, L. 1995, *ApJ*, 445, 367
- Thöne, C. C., de Ugarte Postigo, A., Fryer, C. L., et al. 2011, *Nature*, 480, 72
- Thorne, K. S., & Zytlow, A. N. 1977, *ApJ*, 212, 832
- Zhang, W., & Fryer, C. L. 2001, *ApJ*, 550, 357

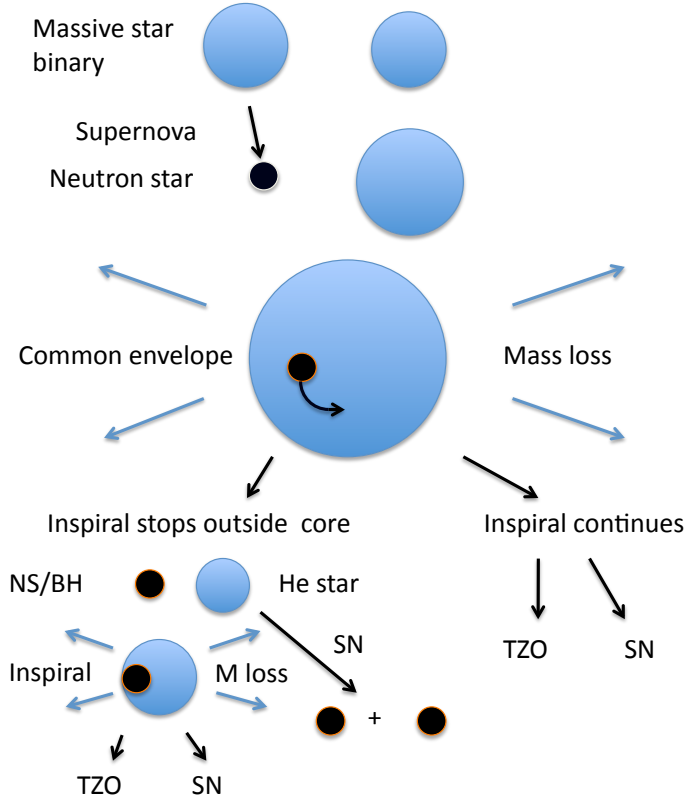


Fig. 1.— The binary evolution possibly leading to supernovae in a dense mass loss region. Here NS is neutron star, BH is black hole, TZO is Thorne-Zytkow object, and SN is supernova. The supernovae of interest here are to the bottom right, where H is present, and to the bottom left, where H is absent.